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Groundwater Contamination in India: Regional Variations, Hydrogeochemical Controls, Health Risks, and Integrated Management Strategies

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Abstract

Groundwater plays a critical role in meeting drinking and agricultural water demands in India. This review focuses on regional variations in groundwater quality, contamination sources, and remediation strategies. The evaluation encompasses pH, electrical conductivity, total dissolved solids, hardness, major ions, and contaminants including fluoride, arsenic, nitrates, and heavy metals. Results reveal significant regional variations, with contamination driven by intensive agriculture, industrial activities, mining, urbanization, and geological factors. Water Quality Index assessments indicate that while many groundwater sources meet drinking standards, numerous sites exceed permissible limits, requiring treatment. Contamination stems from both natural processes (mineral dissolution, rock-water interactions) and anthropogenic activities (fertilizer application, industrial effluents, domestic sewage, mining operations). Health risk assessments demonstrate elevated non-carcinogenic risks in fluoride and nitrate-affected areas, causing fluorosis, Arsenicosis, methemoglobinemia, and other waterborne diseases. Various remediation approaches suitable for Indian conditions have been investigated, including membrane-based systems, electrochemical methods, adsorption techniques, and nature-based solutions. This review provides integrated understanding of India's regional groundwater quality challenges and emphasizes the necessity for targeted interventions, enhanced monitoring, and sustainable management strategies to protect groundwater resources. The review further provides an

integrated regional comparison framework linking contamination sources, hydrogeochemical processes, health risks, and remediation strategies for groundwater management in India.

1. Introduction

1.1 Groundwater Significance in India

Water security in India is largely dependent upon groundwater, as it meets more than 85% of rural drinking water demands and nearly half of the urban water demands (Prasad & Rao,2018, Rajendran et al.,2024). With annual extraction exceeding 230 billion cubic meters, India is the largest user of groundwater worldwide (Kaur et al. 2019). The groundwater system is generally distributed across the major hydrogeological zones like the Indo-Gangetic plains, the Deccan plateau, and the coastal zones. These zones show considerable variations in groundwater quality due to differences in geological environments, climatic conditions, and the extent of human interference (J. A. et al., 2025& Dhakshinamoorthy, Selvarajan, 2025). In the last few decades, the increasing trend of groundwater exploitation, along with the fast pace of industrialization, intensified agricultural activities, and urbanization, has caused a deterioration in water quality (Pandey et al.2023, Pattnaik & Bhowmick, 2020). Water contamination by fluoride, arsenic, nitrate, metals, and salinity has been reported in a significant number of districts of the country, which is a major threat to public health (Kadam et al.2021, Yenugu et al.2020). To overcome these challenges, there is a need for a good understanding of regional patterns of groundwater quality and identification of natural as well as anthropogenic sources of contamination. This knowledge is essential for developing management, protection, and remediation strategies for sustainable use of groundwater in India (Sharma et al. 2021, Kaliyan et al. 2022). This review adopts an integrated approach by linking regional contamination patterns, groundwater chemistry, health risks, and remediation strategies to provide a comprehensive understanding of groundwater quality in India. Unlike earlier review studies that primarily focused on isolated contaminants, localized groundwater quality assessment, or individual hydrogeochemical processes, the present review provides an integrated nationwide synthesis of groundwater contamination in India by combining regional hydrogeochemical variability, contaminant distribution patterns, physicochemical characteristics, human health risks, remediation technologies, and management strategies within a single assessment framework. The review comparatively evaluates contamination trends across major hydrogeological regions of India and incorporates recently published literature up to 2025. In addition, the study emphasizes the interrelationship between contaminant sources, hydrogeochemical controls, health implications, and remediation approaches, thereby providing a broader multidisciplinary perspective useful for researchers, policymakers, and groundwater management agencies.

1.2 Methodology of Review

The present study was conducted as a structured literature review aimed at synthesizing regional groundwater contamination characteristics, hydrogeochemical controls, health risks, and remediation strategies across India. Relevant peer-reviewed literature published between 2000 and 2025 was collected from scientific databases including Scopus, Web of Science, Google Scholar, ScienceDirect, and SpringerLink using keywords such as "groundwater quality India," "fluoride contamination," "arsenic groundwater," "nitrate pollution," "water quality index," and "health risk assessment." Initially, approximately 300 research articles were identified through database searching. After removal of duplicate and irrelevant records, studies were screened based on title, abstract, methodological clarity, and relevance to groundwater quality assessment in India. Studies lacking quantitative groundwater quality data, clear methodological description, or regional relevance were excluded. Finally, 115 studies were selected for detailed review and synthesis.

1.2.1 The inclusion criteria included

(i) Peer-reviewed articles.

(ii) Studies focused on groundwater quality in India.

(iii)Studies reporting physicochemical parameters, contaminant concentrations, health risk assessment, or remediation approaches.

(iv) Studies containing sufficient methodological and analytical information.

1.2.2 The exclusion criteria included

(i) Incomplete datasets,

(ii) conference abstracts without full text,

(iii) studies lacking clear sampling or analytical procedures

(iv) duplicate or non-region-specific reports.

Because of substantial variability in hydrogeological conditions, sampling strategies, analytical methods, temporal scales, and reporting formats among the reviewed studies, the collected information was synthesized qualitatively rather than through formal meta-analysis. The reported concentration ranges and regional trends should therefore be interpreted as indicative comparative assessments rather than statistically aggregated national values. that primarily focused on isolated contaminants, localized case studies, or individual hydrogeochemical processes, the present review attempts to provide a unified nationwide synthesis of groundwater contamination in India by integrating regional hydrogeochemical variability, contaminant sources, health risk implications, remediation technologies, and management strategies within a single assessment framework. The review also incorporates recently published literature up to 2025 and comparatively evaluates contaminant occurrence across major hydrogeological regions of India. This integrated perspective is intended to support researchers, policymakers, and groundwater management agencies in developing region-specific mitigation and sustainable groundwater management strategies. The detailed literature identification, screening, eligibility assessment, and final inclusion process adopted in the present review is illustrated in Figure 1 The review methodology adopted in the present study improves transparency, reproducibility, and comparability of synthesized groundwater quality information across different hydrogeological regions of India.

Table 1. Inclusion and Exclusion Criteria Used for Literature Selection

Criteria Type	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed journal articles	Conference abstracts without full text
Study Area	Groundwater quality studies conducted in India	Non-Indian or non-region-specific studies
Data Requirement	Quantitative groundwater quality parameters and contaminant data	Incomplete datasets
Methodology	Studies with clear sampling and analytical procedures	Studies lacking methodological clarity
optic Relevance	Hydrogeochemistry, contamination, health risk, remediation	Studies unrelated to groundwater contamination
Publication Period	2000–2025	Publications outside selected timeframe

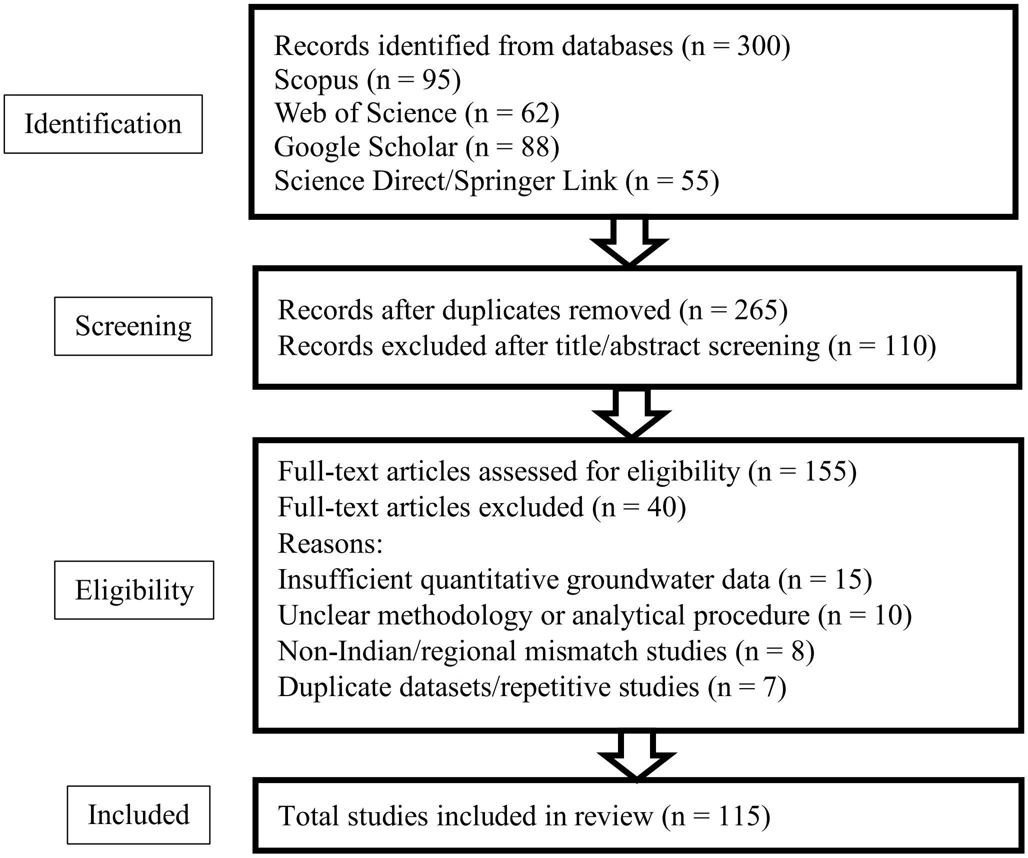

Figure 1. PRISMA-style flow diagram showing literature identification, screening, eligibility assessment, and final study selection process adopted in the present review.

To improve methodological transparency and reproducibility, the literature screening and study selection process was performed using a PRISMA-style framework. The inclusion and exclusion criteria adopted for study selection are summarized in Table 1.

1.3 Research Objectives and Scope.

This review article attempts to collate and assess the available literature for the evaluation of groundwater quality in different regions of India. The main objectives of the study are to identify the regional variability in the physicochemical properties and concentration of major pollutants in groundwater. The study also attempts to identify the natural and anthropogenic sources of groundwater pollution, along with the health hazards that may result from the consumption of polluted groundwater. The review also attempts to identify the most commonly used water quality standards, indexing techniques, and treatment options that are applicable in the context of India. The main advantage of the review article lies in the identification of the available literature and the valuable information that could be obtained for the better management of groundwater resources in India (Shukla & Saxena 2021, Hossain et al.2021). Although emerging contaminants such as pharmaceuticals, PFAS, pesticides, antibiotic residues, and microplastics are increasingly recognized as potential groundwater pollutants, the present review primarily emphasizes conventional inorganic contaminants because of their widespread occurrence, stronger data availability, and greater public health significance in the Indian context.

2. Regional Groundwater Contamination Patterns

2.1 North India.

The groundwater quality problems in North India are diverse, particularly in the Indo-Gangetic Plain. In Punjab and Haryana, intensive agricultural activities have led to groundwater contamination. In these areas, high nitrate concentrations, i.e., above 45 mg/L, have been recorded in 40-60% of groundwater samples, primarily due to the overuse of chemical fertilizers (Saha & Pal, 2025, Raja & Neelakantan, 2021). In the Malwa belt of Punjab, uranium contamination is a major issue with its level up to 644 µg/L compared to the WHO guideline value of 30 µg/L. The contamination is attributed to the use of phosphate fertilizers as well as geological sources (Tanwer et al. 2023). In Rajasthan, the groundwater is significantly affected by arid and semi-arid climatic conditions. High fluoride levels ranging from 1.5 to 8.5 mg/L and high salinity are commonly reported. These conditions are mainly attributed to high rates of evaporation and dissolution of fluoride minerals and low rates of natural recharge (Kaur & Godara, 2025, Maurya et al. 2025, Dhakate et al. 2022). In the case of Delhi and its surrounding National Capital Region, groundwater is characterized by elevated concentrations of total dissolved solids, hardness, and nitrates, with concentrations of 500 to 2500 mg/L, 300 to 800 mg/L, and 50 to 150 mg/L, respectively. These issues are mainly related to sewage water leakage, industrial waste, and agricultural runoff (Maurya et al. 2021, Singh et al.2024). In Uttar Pradesh, there is a high degree of spatial variability in groundwater quality. In eastern parts of the state, arsenic contamination of groundwater, with concentrations varying between 10 and 500 µg/L, is common, whereas fluoride contamination, with concentrations varying from 1.5 to 6.0 mg/L, is common in the western parts of Uttar Pradesh (Adimalla.2020, Karunanidhi et al.2021). In Jammu and Kashmir, groundwater quality is relatively good, although localized pollution, mainly related to agricultural activities and poor sanitation, has been reported in certain areas of the valleys (Chakraborty et al. 2021). The variability in groundwater contamination in North India is mainly regulated by the interaction of agricultural practices, hydrogeology, and urbanization. The nitrate concentration in the groundwater of Punjab and Haryana is strongly influenced by the excessive application of fertilizers (Saha & Pal. 2025& Raja & Neelakantan 2021, Marghade et al. 2021). The presence of uranium in the Malwa region is regulated by both geochemical and fertilizer components (Tanwer et al. 2023). Arsenic in the groundwater of the eastern part of Uttar Pradesh is regulated by reductive dissolution in the alluvial aquifers (Adimalla.2020, Karunanidhi et al. 2021). It is concluded that groundwater quality is location-specific and is regulated by both geochemical and anthropogenic factors.

2.2 South India.

In South India, groundwater is mostly linked with hard rock aquifer systems that are recognized to exhibit specific hydrogeochemical signatures. In Tamil Nadu State, fluoride contamination is widespread, with fluoride levels ranging from 1.5 to 12 mg/L covering 15 districts. The maximum fluoride levels are reported from Salem, Dharmapuri, and Krishnagiri districts due to the weathering of fluoride-bearing granites and gneisses (Ramalingam et al.2022, Ramajayam et al. 2024). Seawater intrusion is another major problem reported from the coastal areas of Tamil Nadu State, where the chloride level is above 1000 mg/L and electrical conductivity is above 3000 µS/cm, extending up to 5-10 km inland (Ramajayam et al. 2024, Singh et al. 2024). The groundwater quality in Karnataka state has been found to vary in different agro-climatic zones. In the northern districts of the state, the groundwater exhibits elevated concentrations of fluoride (2–8 mg/L) and nitrate (50–200 mg/L), whereas salinity intrusion is a major problem in the coastal districts (Sarma & Singh.2023, Taloor et al.2023). In the Bangalore urban region, the groundwater has been found to be contaminated by elevated concentrations of nitrate (45–120 mg/L), the presence of heavy metals such as iron, manganese, lead, and chromium, and bacterial contamination. The causes of groundwater contamination in this region include industrial activities and the lack of proper sewage treatment systems (Panneerselvam et al.2021, Biswas et al. 2023). Andhra Pradesh and Telangana states have reported widespread fluoride contamination in various districts, ranging from 1.5 to 9.5 mg/L. The problem is more acute in districts like Nalgonda, Prakasam, and Guntur (Goyal et al. 2025, Karanveer et al. 2022). In the state of Kerala, the groundwater in the coastal region is highly affected by seawater intrusion. Chloride levels above 1500 mg/L have been reported in about Approximately 30–40% of groundwater wells located within 2 km of the coastline have reported elevated salinity and chloride concentrations due to seawater intrusion. (CGWB.2017). Inland regions of the state have shown better groundwater quality, although some instances of water pollution by agricultural and domestic waste disposal have been reported (Sane et al. 2025). Puducherry has reported high salinity levels, ranging from 1000 to 3500 mg/L in terms of TDS, along with nitrate levels ranging from 50 to 180 mg/L due to the high intensity of agricultural activities in the region (Subramaniyan & Ganesan. 2024). The regional variation in groundwater quality in South India is controlled by hard rock aquifer systems, climatic conditions, and coastal processes. For instance, elevated concentrations of fluoride in groundwater are linked to increased water-rock interaction in granitic rocks (Ramalingam et al. 2022, Singh et al.2020, Adimalla et al.2020). whereas salinity in coastal groundwater is controlled by excessive groundwater abstraction and hydraulic imbalance (Singh et al. 2024, Sarma &

Singh, 2023). In some cities like Bangalore, elevated nitrate concentrations are observed and heavy metals due to poor management of wastewater (Panneerselvam et al. 2021, Biswas et al. 2023). These are examples of the effects of geology, urbanization, and coastal processes on groundwater quality.

2.3 East India.

Eastern India has a very serious groundwater quality problem, which is mainly in the form of arsenic contamination. This problem is particularly acute in the West Bengal region, where arsenic has been found in 79 blocks in nine districts. The concentration of arsenic has been found to vary from 10 to as high as 3200 µg/L, which is well above the WHO guideline value of 10 µg/L (Mukherjee et al.2015 & Sabinaya et al.2023 & Khan et al. 2021). The source of arsenic in the groundwater in the eastern part of India is natural. Geological processes are responsible for the occurrence of arsenic in the groundwater in the eastern part of India. The reducing conditions in the alluvial aquifer allow the release of arsenic from iron oxyhydroxide into the groundwater (Malik et al. 2021). A similar trend has been observed in the Bihar region, where arsenic contamination has been reported in about 15 districts, with a maximum concentration of 1800 µg/L (Sahu et al. 2017). In Jharkhand, the groundwater quality is highly affected by mining activities. In areas where coal mining, iron ore mining, and industries are prevalent, high concentrations of heavy metals such as iron, manganese, lead, cadmium, chromium, copper, and zinc have been recorded (Panneerselvam et al. 2023 & Reddy et al.2022). In addition, fluoride contamination has been recorded in the western districts, where the concentration of fluoride varies from 1.5 to 6.5 mg/L, primarily due to geological factors (Singh et al. 2022). In Odisha, a significant variation in groundwater quality has been recorded. In the coastal areas, salinity intrusion is a major problem, whereas in the western districts, fluoride concentrations vary from 2 to 7 mg/L, and areas near mining and industrial activities have high concentrations of heavy metals (Kouser et al.2022). The quality of groundwater in Assam and other states in the northeastern region tends to be better, considering the high rainfall and good recharge conditions. Yet, there are some reported cases of contamination in the tea estate areas, oil refineries, and in places with poor sanitation facilities (Basha et al.2022). At some places, the iron and manganese content in the groundwater also exceeds the permissible limits of 0.3 mg/L and 0.1 mg/L, respectively, mainly because of the reducing conditions in the aquifers. (Singh et al.2022) The major processes controlling groundwater contamination in eastern India are geogenic in nature, dominated by arsenic contamination in reducing environments in alluvial aquifers (Mukherjee et al.2015, Sabinaya et al., 2023, Khan et al., 2021). In contrast to western and southern India, where groundwater contamination is dominated by fluoride, eastern India has its own set of groundwater contamination processes, dominated by sedimentary geology and redox chemistry (Malik et al.2021, Sahu et al. 2017).In addition, there is heavy metal contamination in Jharkhand due to mining activities, which clearly indicates anthropogenic influences on groundwater chemistry (Panneerselvam et al., 2023 , Reddy et al.2022).

2.4 West India

Significant variations in the quality of groundwater in Western India have been observed. In Gujarat, various problems in the quality of groundwater have been reported. Fluoride contamination in the range of 1.5 to 10 mg/L has been reported in ten districts. The coastal areas in the Saurashtra and Kutch districts are also affected by salinity intrusion, where the TDS level ranges from 1500 to 5000 mg/L. Moreover, areas where agricultural activities are concentrated also face problems of nitrate contamination in the range of 50 to 300 mg/L (Yadav et al.2018, Dhanya Raj & Shaji, 2017, Shaikh et al., 2020). Groundwater contamination by heavy metals like chromium, lead, cadmium, and nickel has been reported in the industrial areas around Ahmedabad, Vadodara, and Surat cities, which is attributed to the effluent discharge from the textile, chemical, and pharmaceutical industries (Srinivas et al. 2013). Groundwater quality in Maharashtra exhibits significant spatial variability influenced by geological and anthropogenic factors In Vidarbha and Marathwada, the presence of fluoride ranges between 2-8 mg/L. Nitrate-related problems are present in areas with sugarcane cultivation, ranging between 50-250 mg/L. (Mhaske et al. 2022, Naskar et al., 2025). Regions with industries have higher levels of heavy metals in groundwater. In Mumbai and other major cities, the issue of total dissolved solids, hardness, and bacterial presence are major problems, and these are mainly caused by leakage in the sewage system and industries (Wagh et al.2019). In the state of Goa, the presence of seawater in the groundwater of the coastal areas ranges between 40-50% with chloride levels above 2000 mg/L within 3 km of the shoreline (Sidhu et al.2024). In the western part of India, the groundwater quality is affected by the arid climatic conditions, the high intensity of agriculture, and industrialization. elevated fluoride and salinity concentrations in groundwater samples are related to evaporation and the dissolution of minerals (Yadav et al.2018, Dhanya Raj & Shaji. 2017, Shaikh et al.2020). elevated concentrations of nitrate in groundwater samples reflect the impact of agricultural activities (Shaikh et al.2020). Industrialization has affected the groundwater quality in the form of heavy metals in the urban areas (Srinivas et al. 2013). The impact in the western part of India is a mix of geogenic and anthropogenic factors compared to the eastern part.

2.5 Central India

Groundwater in Central India reflects the fingerprints of nature as well as human activities. In Madhya Pradesh, the presence of fluoride poses a problem in several areas, ranging from 1.5 to 7.5 mg/L over 14 districts of the state. The districts of the Malwa Plateau and Vindhyan areas are of particular concern, and the cause of the problem is the weathering of those minerals containing fluoride (Karunanidhi et al. 2021, Vijayakumar et al.2021). Nitrate contamination of groundwater occurs in several agricultural districts, where the excessive use of chemical fertilizers is the major cause of the problem, with nitrate concentrations ranging from 50 to 180 mg/L (Alam et al. 2024). In the state of Chhattisgarh, the groundwater scenario reflects the impact of mining and industries. In the state, heavy metals like iron, manganese, chromium, lead, and cadmium are present in groundwater at elevated concentrations, often two to ten-fold higher than the permissible limits (Saw et al.2022, Ullengula et al. 2026). In the coal mining areas, sulphate concentrations are significantly elevated, ranging from 200 to 600 mg/L, and TDS concentrations are also elevated, ranging from 1000 to 3000 mg/L, mainly because of Acid mine drainage (Karunanidhi et al.2020). In the agricultural areas, nitrate contamination of groundwater occurs, with concentrations ranging from 45 to 150 mg/L, mainly because of the application of fertilizers and the disposal of organic waste (Ambade et al.2024). The figure represents the Groundwater Contamination Hotspots in India. The quality of groundwater in central India is characterized by various geological formations and anthropogenic activities like mining and agricultural activities Higher concentrations of fluoride ions are related to the weathering of minerals, whereas heavy metal contamination is mainly related to mining activities. Compared to other regions, central India is characterized by mixed contaminant patterns due to various natural and anthropogenic factors. The map highlights dominant groundwater contamination zones reported in reviewed studies, including arsenic contamination in eastern alluvial aquifers, fluoride enrichment in western and southern hard-rock terrains, nitrate contamination in agriculturally intensive northern regions, salinity intrusion in coastal aquifers, and heavy metal contamination near mining and industrial zones.

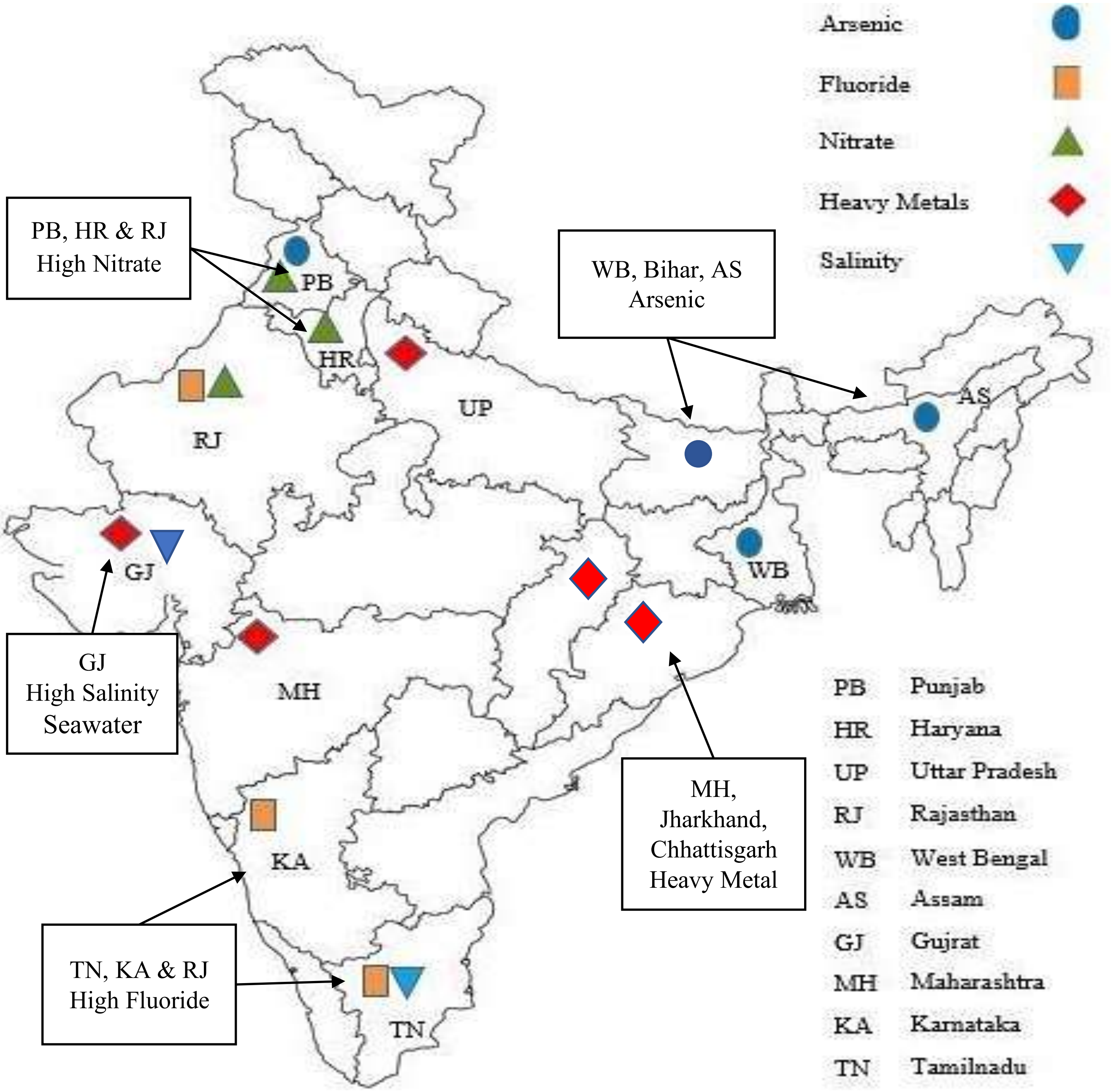

Figure 2. Regional distribution of major groundwater contaminants across India showing dominant fluoride contamination in western and southern states, arsenic occurrence in eastern alluvial plains, and nitrate enrichment in agriculturally intensive regions.

2.6 Comparative Regional Analysis

A regional perspective of groundwater contamination in India shows varying degrees of contamination. In the northern part of India, the major groundwater contamination problems are related to nitrates and uranium. These are primarily related to agricultural activities and fertilizer usage. In the western and southern parts of India, fluoride and salinity are major groundwater contamination problems. These are related to geological and climatic factors. In the eastern part of India, arsenic contamination is a major problem, and this is primarily related to geological factors. In central India, heavy metals are a major groundwater contamination problem, and this is primarily related to mining activities (Saraswat et al. 2023, Khan et al. 2021). A comparative evaluation of groundwater quality in various regions of India has shown specific patterns of groundwater quality in different regions. Northern and western regions exhibit contamination patterns dominated by nitrate and fluoride, respectively, due to agricultural activities and climatic conditions (Yadav et al.2018, Dhanya Raj & Shaji. 2017, Shaikh et al. 2020). The eastern parts of India are affected by arsenic contamination (Malik et al. 2021). whereas in southern India, both fluoride and salinity are major groundwater quality problems (Ramalingam et al. 2022). In central India, mining activities are responsible for heavy metal contamination (Saw et al. 2022, Ullengula et al. 2026). The results show that groundwater contamination is region-specific. The regional variations in groundwater quality discussed above can be seen in terms of physicochemical properties of groundwater, which are discussed in detail in the next section. The variations discussed here show how geology and human activities affect groundwater chemistry in various parts of India.

Table 2: Regional Groundwater Quality Parameters Across Major Indian Locations

State	pH	EC (µS/cm)	TDS (mg/L)	TH (mg/L)	F^- (mg/L)	NO_3^- (mg/L)	As (µg/L)	Primary Concerns	Authors
Punjab	7.2-8.5	800-3500	500-2200	300-900	0.5-2.5	45-250	5-644	Nitrate, Uranium	Saha&Pal.2025, Raja& Neelakantan.2021, Marghade et al. 2021
Rajasthan	7.0-8.8	1200-5500	750-3500	400-1500	1.5-8.5	20-120	<10	Fluoride, Salinity	Kaur & Godara, 2025, Maurya et al.2025, Dhakate et al.2022
Delhi NCR	7.1-8.3	900-4000	600-2500	300-800	0.3-2.0	50-150	<10	TDS, Nitrate, Hardness	Maurya et al.2021, Singh et al.2024
Tamil Nadu	6.8-8.6	800-4500	500-3000	250-1200	1.5-12.0	30-180	<10	Fluoride, Salinity	Ramalingam et al.2022, Singh et al.2020, Adimalla

									et al. 2020
Karnataka	6.5-8.4	700-3800	450-2400	200-950	2.0-8.0	50-200	<10	Fluoride, Nitrate	Sarma& Singh.2023 , Taloor et al. 2023
West Bengal	6.8-7.8	600-2500	400-1600	200-700	0.2-1.5	20-80	10-3200	Arsenic, Iron	Mukherjee et al. 2015, Sabinaya et al.2023, Khan et al.2021
Bihar	6.9-7.9	650-2800	420-1800	220-750	0.3-2.0	25-90	10-1800	Arsenic, Fluoride	Sahu et al.2017
Gujarat	7.0-8.7	1000-6000	650-4000	300-1800	1.5-10.0	50-300	<10	Fluoride, Salinity, Nitrate	Yadav et al., 2018, Dhanya Raj & Shaji.2017, Shaikh et al.2020
Maharashtra	6.8-8.5	750-4200	480-2700	250-1100	2.0-8.0	50-250	<10	Fluoride, Nitrate	Mhaske et al.2022, Naskar et al.2025
Madhya Pradesh	7.0-8.6	800-3600	520-2300	280-950	1.5-7.5	50-180	<10	Fluoride, Nitrate	Karunanidhi et al. 2021, Vijayakumar et al 2021, Alam et al.2024
Chhattisgarh	6.5-8.2	700-3500	450-2200	240-900	0.5-3.0	45-150	<10	Heavy Metals, Nitrate	Saw et al. 2022, Ullengula et al.2026, Karunanidhi et al.2020
Odisha	6.7-8.3	650-3800	420-2400	220-950	2.0-7.0	30-120	<10	Fluoride, Heavy Metals	G. et al. 2024 Kouser et al.2022

Table 2 The values presented are compiled from multiple studies corresponding to the cited references for each region. To provide a clearer regional comparison supported by literature, of India.

Note: The concentration ranges presented in Table 2 represent compiled minimum–maximum ranges reported in the reviewed literature for different groundwater quality parameters across selected regions of India. The values are synthesized from multiple independent studies conducted under varying hydrogeological, seasonal, and analytical conditions and should therefore be interpreted as indicative comparative ranges rather than standardized regional averages.

Table 3: Comparative Regional Summary of Groundwater Contamination in India

Region	Dominant Contaminants	Typical Concentration Range	Key Causes	Severity Level	Authors
North India	Nitrate, Uranium	NO_3^- 50–150 mg/L	Fertilizers, agriculture	High	Saha & Pal. 2025, Chakraborty et al. 2021
South India	Fluoride, Salinity	F^- 2–12 mg/L	Rock-water interaction, coastal intrusion	High	Ramalingam et al.2022, Subramaniyan &Ganesan. 2024
East India	Arsenic	As 10–3200 µg/L	Reductive dissolution (geogenic)	Very High	Mukherjee et al.2015, Singh et.al.2022
West India	Fluoride, Nitrate, Salinity	F^-2–10 mg/L	Arid climate, agriculture	High	Yadav et al.2018, Sidhu et al. 2024
Central India	Fluoride, Heavy Metals	F^-1.5–7 mg/L	Mining, geology	Moderate–High	Karunanidhi et al. 2021,

					Ambade et al. 2024

Table 3 Summarizes dominant contaminants, their typical ranges, and associated causes across different regions.

Note: The contaminant concentration ranges summarized in Table 3 represent indicative ranges compiled from published regional groundwater studies. The values reflect reported concentration intervals from different hydrogeological settings and are intended for comparative regional assessment rather than direct statistical comparison.

The comparative analysis suggests that the arsenic contamination in eastern India poses the highest health risk in terms of toxicity and prevalence, while the fluoride contamination in the western and southern regions has a larger population affected. Nitrate contamination in India has moderate to high spatial variability and is associated with agricultural regions. These comparisons provide a semi-quantitative evaluation of the severity of groundwater contamination in India.

3.Hydrogeochemical Characteristics and Contamination Mechanisms

3.1 pH

Groundwater pH in India ranges from a neutral to mildly alkaline level, usually between 6.5 and 8.8 (Krishnappa et al.2024). If the pH level increases to above 8.0, then it is probably in the arid and semi-arid zones, where evaporation causes the dissolution of carbonate minerals. If the rainfall is significantly elevated or in areas where mines are present, then the pH level may turn slightly acidic (Shirke et al.2020). The level of pH is a very significant factor, as it influences the movement of metals, the interaction of minerals, and the treatment process (Saha et al.2024).

3.2 Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The range for groundwater conductivity is normally between 600 and 6000 µS/cm, which is equivalent to a TDS of about 400 to 4000 mg/L (Hanse et al.2019). Increased levels of electrical conductivity and TDS imply an increased amount of dissolved ions, often resulting from mineral weathering, evaporation, and human activities such as farming and industrial operations (Mukherjee & Singh. 2022). Research carried out in various parts of India has indicated that about 40% of the groundwater has TDS levels above the permissible limit of 500 mg/L (Sahoo et al. 2024; Mukherjee & Singh, 2022). (Sahoo et al.2024, Mukherjee & Singh, 2022).

3.3 Total Hardness (TH).

The range of total groundwater hardness is 200 to 1800 mg/L as CaCO3. Reviewed regional studies have reported that approximately 40–60% of groundwater samples in several investigated regions of India fall within the hard to very hard category. with values above 300 mg/L (Ravindra & Mor, 2019). The high level of groundwater hardness is attributed to the elevated concentrations of calcium and magnesium ions that are dissolved from rocks such as limestone, dolomite, and gypsum (Adimalla et al.2018). Although the level of water hardness is not a health hazard, high levels can cause pipe scaling and could possibly contribute to heart problems (Ahada & Suthar, 2019). Dissimilarities in methodologies for analysis applied in different studies, including differing limits of detection and types of instrumentation (e.g.ICP-MS vs. AAS), as well as sample preservatives applied, may also contribute to differing results. These methodological dissimilarities may add to the uncertainty in results (Hanse et al.2019, Mukherjee & Singh.2022).

3.4 Major Cations and Anions.

Cations

Calcium and magnesium are the major cations present in Indian groundwater. The concentration of calcium ranges from 40-450 mg/L, while magnesium ranges from 20-280 mg/L. The major source of calcium and magnesium is mineral weathering, i.e., carbonate and silicate mineral weathering (Mawari et al. 2022). The concentration of sodium ranges from 20-800 mg/L, while potassium ranges from 2-50 mg/L. However, in arid areas, coastal areas, and areas of heavy agricultural activity, higher concentrations of sodium and potassium have also been reported, primarily due to evaporation, intrusion of seawater, and extensive use of chemical fertilizers (Mukherjee et al.2019).Higher concentrations of sodium also pose a major problem, as it reduces soil permeability and can be harmful to human health, especially for people suffering from hypertension (Yadav et al.2019).

Anion

The most common negatively charged ions present in groundwater are bicarbonate ions. The range of bicarbonate ions is between 150 to 800 mg/L. The bicarbonate ions are generally derived from the dissolution of carbonate minerals and the action of carbon dioxide (Ahada & Suthar. 2018). The level of chloride ions is generally between 20 to 2000 mg/L. The level of chloride ions is high in coastal areas where seawater intrusion occurs, dry areas where salts are present due to evaporation, and areas where sewage leakage is observed (Hussain et al.2012). The level of sulphate ions is generally between 20 to 600 mg/L. The level of sulphate ions is derived from the dissolution of gypsum minerals and industrial waste as well as acid mine drainage (Madhavan et al.2023). Around 35-45% of groundwater samples from highly intensive agricultural areas such as Punjab, Haryana, and Gujarat show nitrate levels above the permissible limit of 45 mg/L. Conversely, in less intensive areas, the levels of exceedance are low. This may be due to the variation in the application of fertilizers (Chaudhry & Sachdeva.2021).

3.5 Heavy Metals and Trace Elements

Fluoride.

There are reports of the presence of fluoride in groundwater in many parts of India, with concentrations ranging from 1.5 to 12 mg/L. This problem occurs in several districts across several states, affecting millions of people (Das et al. 2009). The primary sources of fluoride in groundwater are the weathering of minerals like fluorite, apatite, and mica, all of which are present in the environment in granitic and gneissic rocks (Ghosh et al.2024). Groundwater chemistry, like pH, calcium, and bicarbonate, also contributes to the presence of fluoride in groundwater (Gupta et al. 2019).

Arsenic

Among the major groundwater pollutants, arsenic is particularly notable in India, and its concentration in water varies sharply, from a minimum of 10 µg/L to a maximum of 3200 µg/L, with particularly elevated concentrations of contamination detected in states such as West Bengal, Bihar, Uttar Pradesh, Assam, and Chhattisgarh (Gupta et al.2015).The major source of arsenic entering groundwater is the reductive dissolution of iron oxyhydroxides, particularly in anaerobic and alluvial aquifer systems (Cherukumilli et al. 2018). In groundwater, arsenic is observed in two forms, arsenite (As^{3+}) and arsenate (As^{5+}). Arsenite is more mobile and toxic than arsenate (Inaniyan & Raychoudhury, 2019).

Other heavy metals

Iron and manganese are often present in groundwater samples in concentrations higher than the safety limits, especially in areas where the environment of the aquifer is reducing. In these areas, iron concentrations vary between 0.1 and 15 mg/L, and manganese concentrations vary between 0.05 and 5 mg/L. These two elements are often present together and can cause problems with the colour and taste of the water, as well as health risks (Koley, 2021). Other heavy metals, like lead (5-150 µg/L), cadmium (2-50 µg/L), chromium (10-500 µg/L), copper (10-200 µg/L), and zinc (50-1000 µg/L), are usually reported in areas near industrial centres, mining areas, and areas with intensive agricultural activities, as these are the areas where human activities are the strongest (Singh et al.2024 , Awasthi et al.2021).Drinking water with these heavy metals can cause health problems like neurological disorders, kidney problems, and cancer (Khandaker & Rahman.2022). The figure represents the comprehensive seven-phase water quality assessment methodology employed for groundwater quality evaluation and Their Significance**.**

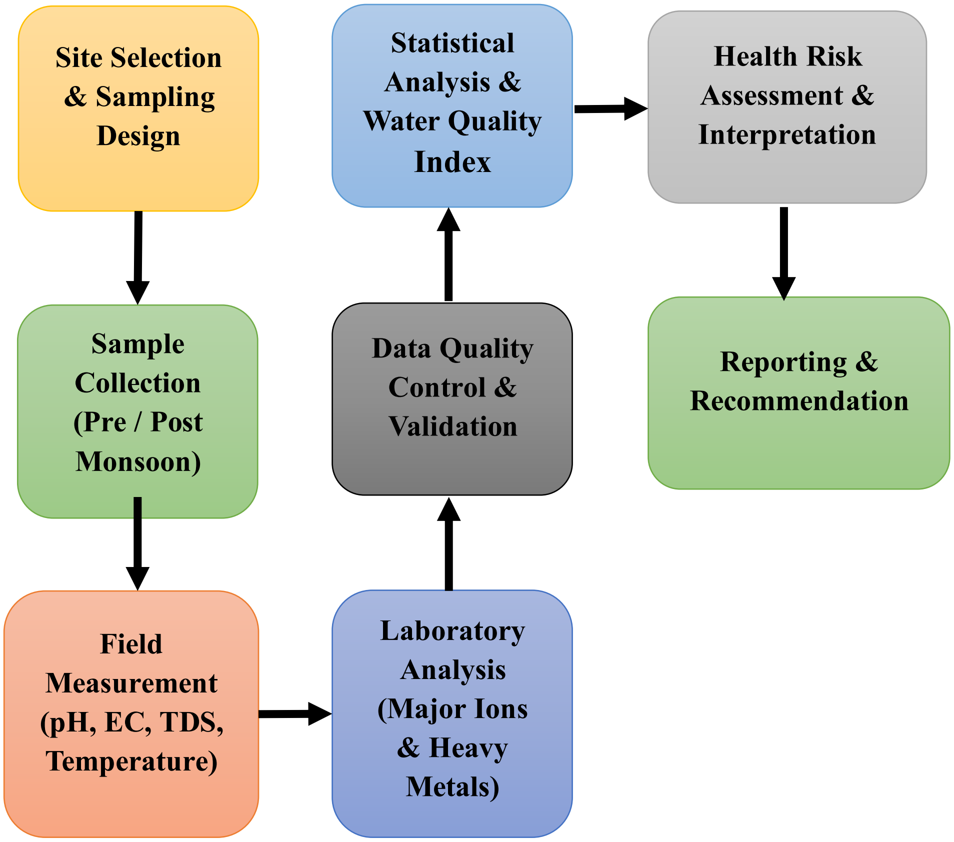

Figure 3. Integrated methodological workflow adopted for groundwater quality assessment, hydrogeochemical interpretation, health-risk evaluation, and remediation strategy selection in Indian groundwater studies.

The assessment workflow presented in Figure 3 demonstrates the importance of integrating field sampling, laboratory analysis, water quality indexing, hydrogeochemical interpretation, and health risk assessment for comprehensive groundwater quality evaluation. The figure indicates that groundwater assessment should not rely solely on physicochemical parameter measurement, but should also include interpretation of contaminant sources, exposure pathways, and associated human health implications. This integrated assessment approach improves the reliability of groundwater quality evaluation and supports region-specific groundwater management strategies.

Nutrients and Emerging Contaminants

One of the most common nutrient pollutants in India's groundwater is nitrate. The primary sources of nitrate contamination are fertilizers, animal waste, and sewage. Nitrate contamination of groundwater is a major issue, as it has been reported that almost 40% of groundwater in highly cultivated areas exceeds permissible limits, although this is not so prevalent in areas with less agricultural activity (Marghade et al. 2023). In India, the normal concentration of phosphates in groundwater is within a range of 0.1 to 5 mg/L. An increase in phosphates is a sign of organic pollution, which may result in eutrophication in water bodies that are connected to the groundwater (Wintgens et al.2015). In recent times, there has been a surge of interest in newer pollutants, including pesticides, pharmaceuticals, and microplastics, in India's groundwater. However, there is limited information on the sources, occurrence, and potential impact of these pollutants on India's groundwater (Pal et al. 2009, Sultan et al. 2024). In recent years, increasing concern has also been raised regarding emerging contaminants such as pesticide residues, pharmaceutical compounds, personal care products, antibiotic residues, PFAS (per- and polyfluoroalkyl substances), endocrine-disrupting compounds, and microplastics in groundwater systems. These contaminants primarily originate from agricultural runoff, untreated sewage discharge, landfill leachates, industrial effluents, hospital wastewater, and improper disposal of domestic and pharmaceutical waste. Although systematic nationwide data for these contaminants in Indian groundwater remain limited, several localized investigations have reported detectable concentrations in urban, peri-urban, and agriculturally intensive regions. Long-term exposure to such contaminants may pose ecological risks, antimicrobial resistance concerns, endocrine disruption, and chronic human health impacts. However, due to limited monitoring data, inconsistent analytical methods, and lack of standardized national datasets, the present review mainly focuses on conventional inorganic groundwater contaminants such as fluoride, arsenic, nitrate, salinity, and heavy metals, which remain the most widely reported and critical groundwater quality concerns across India.

3.6 Contamination Sources

The diagram identifies the various sources of contaminations that affect the groundwater in India. The sources include runoff from agriculture, which contains fertilizers and pesticides; industrial waste, which contains heavy metals and chemical compounds; domestic sewage, which contains nutrients; mining, which results in acid and the release of metals; and geogenic sources, which contain fluoride and arsenic compounds that are released from the interaction between rocks and water. The pathways that are represented in the diagram include infiltration, leaching, and lateral movement from surface water bodies. It is worth noting that the variations in the reported values of groundwater quality from various sources may be attributed to various factors. For example, some sources may have been based on single-time sampling, while others may have been based on seasonal sampling. This may have caused inconsistencies in the reported values. It is significant to note that the groundwater quality data collected and compiled in this review have been obtained from various studies conducted over different time periods, hydrogeological settings, and methodological approaches. These factors can have a major impact on the data. For example, groundwater samples collected before the monsoon season have shown high concentrations of contaminants (Krishnappa et al. 2024, Shirke et al.2020). whereas samples collected after the monsoon season have shown low concentrations (Sahoo et al.2024). Similarly, alluvial aquifers have shown different geochemical characteristics compared to hard rock aquifers (Mawari et al.2022). Therefore, direct comparison of values across studies should be interpreted cautiously. The variation in physicochemical parameters and contaminant concentrations is related to both natural and anthropogenic sources. This is significant in understanding the patterns of groundwater chemistry discussed above. Figure 4 demonstrates that groundwater contamination pathways in India are highly interconnected. Agricultural runoff contributes primarily to nitrate and pesticide contamination, while industrial effluents are major sources of heavy metals and toxic chemicals. Geogenic contamination pathways differ significantly from anthropogenic pathways because they are strongly controlled by aquifer mineralogy and groundwater chemistry. The figure further highlights that contaminant migration occurs through infiltration, leaching, and groundwater flow processes, emphasizing the importance of hydrogeological conditions in contaminant transport

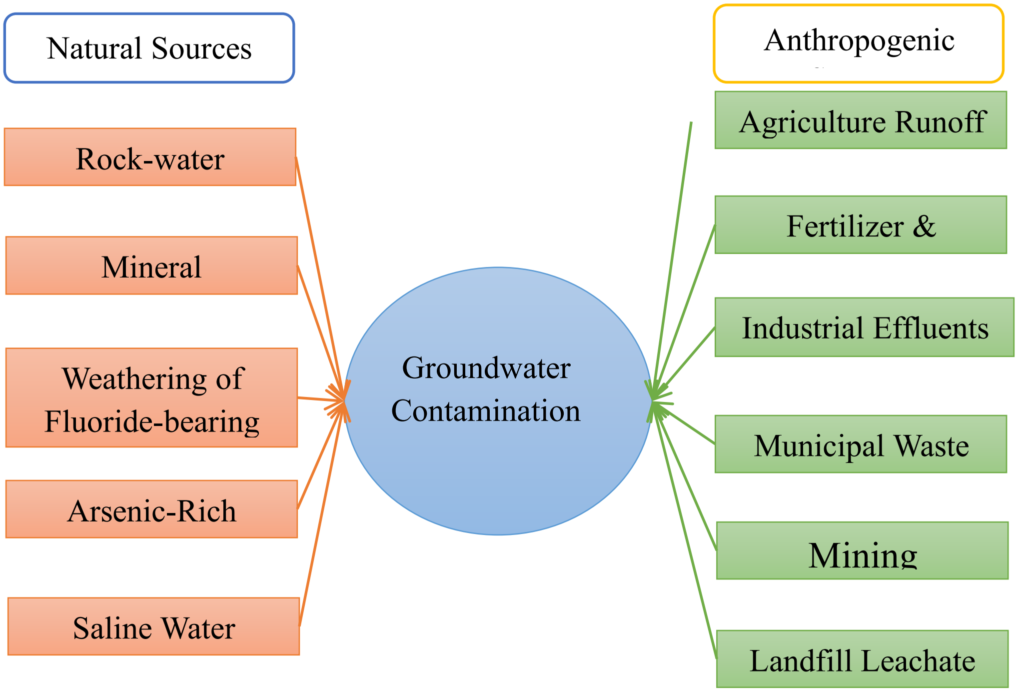

Figure 4: Major geogenic and anthropogenic groundwater contamination sources and contaminant transport pathways in Indian aquifer systems. (synthesized from literature).

3.7 Natural Geogenic Sources

Water can also be contaminated by natural geological and hydrogeochemical processes. Fluoride concentration increases due to the weathering of fluoride-bearing minerals like fluorite, apatite, biotite, and hornblende, which are present in rock formations of granite, gneiss, and volcanic origins (Malik et al. 2023). Also, groundwater with an alkaline nature (pH above 7.5), low calcium content, and high bicarbonate and sodium levels is more likely to dissolve more fluoride and move it around (Barathkumar et al. 2025). As for the issue of arsenic contamination, it is mostly associated with alluvial aquifers where iron and manganese oxyhydroxide dissolution occurs reductively under anaerobic condition (Cherukumilli et al. 2017). Microbial processes also enhance the degradation rate of organic matter and alter geochemical conditions, moving towards more reducing conditions, which in turn increases the release of arsenic in groundwater (Kalaiselvi & Pillai, 2019). Under arid and semi-arid conditions, salinity problems are mainly driven by the rapid rate of evaporation, the dissolution of salt minerals such as halite and gypsum, and the lack of recharge to groundwater (Vijaylaxmi & Khan, 2021). For example, in coastal aquifers, seawater intrusion occurs due to the pumping of groundwater, which changes the hydraulic gradients and causes seawater to flow inland (Saha et al.2014). Heavy metals such as iron, manganese, uranium, and thorium are found in specific geological formations and are transported through groundwater depending on parameters such as pH and redox reactions (Karunanidhi et al. 2024)

3.8 Anthropogenic Sources

Agricultural activities.

Agricultural practices in most areas of India also contribute significantly to the contamination of groundwater. This is particularly so because of the extensive use of chemical fertilizers, which increases the nitrate and phosphate content in the water (Kumar et al.2017). The use of pesticides, coupled with irrigation return flows, further contributes to the degradation of the water quality. Moreover, in areas such as Punjab, Haryana, and Gujarat, the nitrate content in the water is above 100 mg/L, which is attributed to the extensive use of nitrogen fertilizers in these areas (Mandal & Sanyal.2019). Livestock and poultry farming also contributes to the contamination of the water table (Narsimha & Sudarshan. 2017).

Industrial effluents

Industrial activities, such as finishing of textiles, chemical, and pharmaceutical products, tanning of leather, electroplating, and mining, also pose a major threat to groundwater. In this sector, heavy metals like chromium, lead, cadmium, nickel, copper, and zinc, along with organic compounds and other toxic chemicals, are being disposed of (Muthusamy et al. 2023). When treatment of effluent is inadequate, and disposal of wastes takes place in unlined areas, it is easy for chemicals to leach into groundwater (Nagaraj & Masilamani. 2023). Consequently, high concentrations of heavy metals are found in industrial areas of Gujarat, Maharashtra, Tamil Nadu, and West Bengal (Bhuiyan&Ray.2017).

Domestic sewage and solid waste

In addition, poor sewage disposal and unreliable sanitation facilities in urban areas also cause groundwater contamination. When untreated sewage enters the ground, it carries nitrates, phosphates, chlorides, and various organic compounds with it, thereby contaminating groundwater (Yasaswini et al.2024). In rural areas, open defecation also causes environmental pollution, leading to contamination of water bodies (Mukherjee et al.2021). Moreover, when solid wastes are disposed of in open dumps, leachate may carry heavy metals, organic compounds, and dissolved solids, thereby contaminating groundwater (Thalod & Sharma.2024).

Mining operation

Mining activities, like coal, iron, and bauxite mining, cause acid mine drainage, suspension of solids, and elevated levels of heavy metals (Panneerselvam et al. 2023). In groundwater, the pollution caused by mining activities runs very deep in the states of Jharkhand, Chhattisgarh, and Odisha (Reddy et al.2022).

3.9 Contamination Pathways and Mechanisms

Groundwater contamination occurs in various forms. Groundwater may be contaminated by seepage from surface sources, downward percolation from the unsaturated zone, and horizontal movement from already contaminated surface sources such as rivers, lakes, and canals. Groundwater may also be contaminated vertically or horizontally along fractures and joints, especially in hard rocks (Cherukumilli et al.2017). Contaminated groundwater does not move in an arbitrary manner; it is influenced by various elements. The behaviour and movement of the contaminant depend on the characteristics of the aquifer, i.e., the ease with which both water and contaminants pass through it (permeability), the available void spaces (porosity), and the minerals that react with the contaminant. Other elements include the hydrogeological characteristics, i.e., the rate at which the water table replenishes, the rate at which the groundwater moves, and the depth at which the water table lies. Finally, there are the characteristics of the contaminant, i.e. its solubility how easily it moves, and the period it lasts in the environment without degrading. All these elements contribute to the behaviour and movement of the contaminant in the aquifer system (Kalaiselvi & Pillai. 2019)

4. Health Implications

This figure 5 depicts the pathway from contamination sources through exposure routes (drinking water, food chain, dermal contact) to health outcomes. It shows acute effects (gastrointestinal illness, methemoglobinemia) and chronic effects (fluorosis, Arsenicosis, cancer, neurological disorders, kidney disease) with vulnerable populations (children, pregnant women, elderly) highlighted. The contamination sources and pathways discussed above directly affect human exposure to polluted groundwater. The presence of pollutants such as fluoride, arsenic, nitrate, and heavy metals in groundwater poses serious health risks, which are discussed in the section below. Figure 5 illustrates the relationship between groundwater contamination exposure pathways and associated human health outcomes. The figure indicates that drinking water remains the dominant exposure pathway for most groundwater contaminants in India. Long-term exposure to fluoride, arsenic, nitrate, and heavy metals contributes to chronic health effects including fluorosis, arsenicosis, neurological disorders, kidney damage, and carcinogenic risks. The figure also highlights that children and elderly populations are more vulnerable because of higher exposure sensitivity and physiological susceptibility.

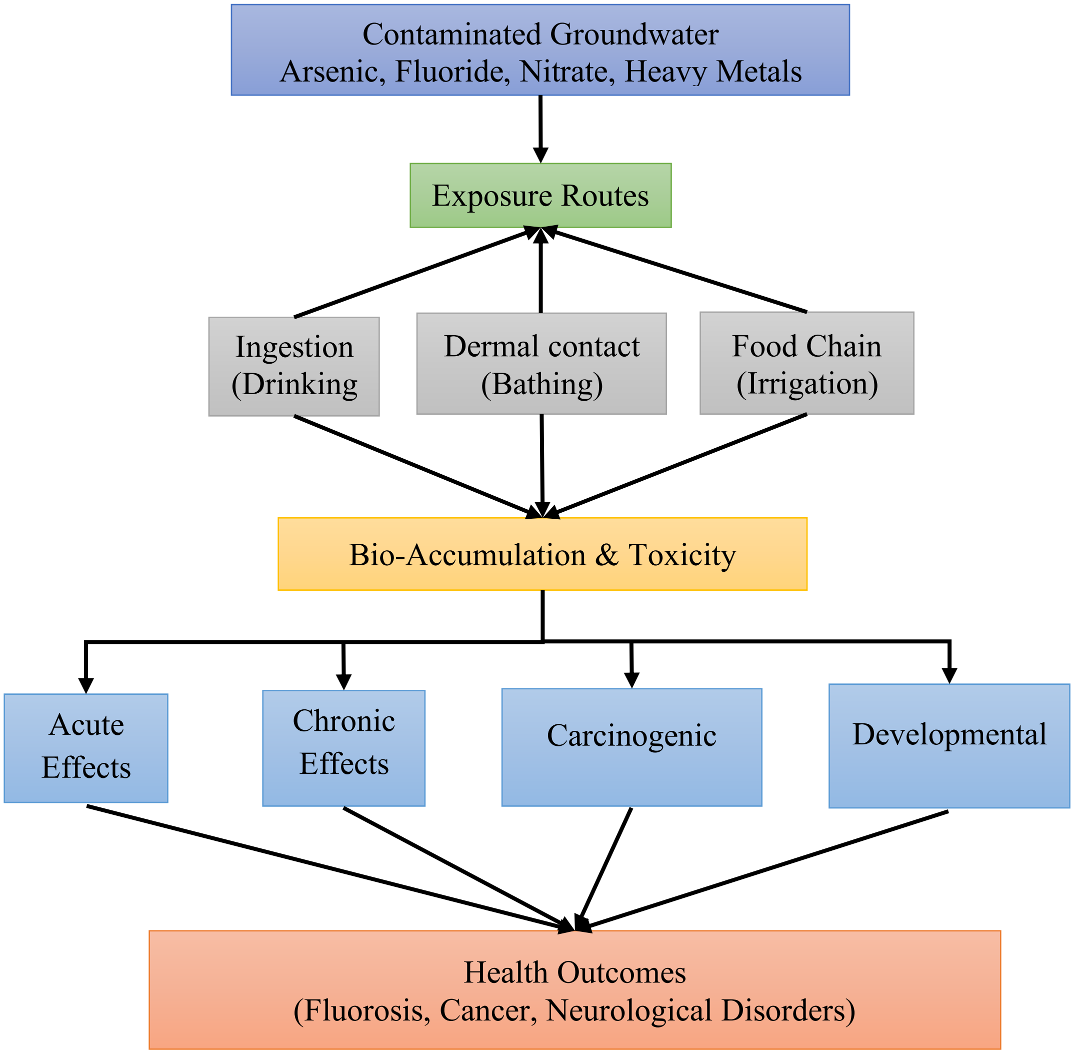

Figure 5. Major groundwater contamination exposure pathways and associated human health impacts in India.

4.1 Health Effects of Major Contaminants

Fluoride

When the amount of fluoride exceeds 1.5 mg/L, there is a high probability of causing fluorosis in both teeth and bones. In the case of teeth, fluorosis causes mottling and discoloration of the teeth, while in bones, it causes changes in the structure of the bones, joint pain, and lack of mobility (Das et al. 2009). In India, there is a high prevalence of fluorosis, and Previous national and regional assessments have estimated that nearly 66 million people in India may be exposed to fluoride-affected groundwater (WHO, 2017; Ghosh et al. 2024). In addition, it causes neurological effects, impacts IQ in children, and causes reproductive problems (Gupta et al.2019).

Arsenic.

Prolonged consumption of drinking water contaminated with arsenic causes a condition referred to as Arsenicosis, which manifests itself in the form of changes in the colour of the skin, keratosis, and other skin lesions (Gupta et al. 2015). Prolonged consumption also increases the risk of cardiovascular problems, neurological problems, diabetes, and various types of cancer, which affect the skin, lungs, bladder, and kidneys. A considerable number of people in eastern India continue to be at risk of arsenic poisoning through the drinking water supplied to them through the taps (Cherukumilli et al. 2018). Among the various compounds of arsenic, arsenite ($As3+$) is found to be more poisonous and mobile than arsenate ($As5+$) (Inaniyan & Raychoudhury, 2019).

Nitrate

Drinking water with nitrate concentration higher than 45 mg/L is particularly hazardous for babies, as it can cause methemoglobinemia, or 'blue baby syndrome,' which impairs the blood's capacity for carrying oxygen [96]. Adults who are frequently exposed to nitrates have a higher probability of developing gastric, thyroid, and reproductive system diseases (Kumar et al.2017). In areas with heavy agricultural activity, there is a higher incidence of diseases associated with nitrate poisoning (Mandal & Sanyal,.2019).

Heavy Metals

The risk of health hazards from heavy metals in groundwater is a fact. Lead affects the nervous system, resulting in a drop in IQ, behavioural problems, and kidney damage (Singh et al.2024). Cadmium causes a buildup of the metal in the kidneys, resulting in renal failure and bone disease (Awasthi et al.2021). Hexavalent chromium is a known carcinogen and causes lung and digestive cancers (Khandaker & Rahman.2022) Iron and manganese, although essential, in high concentrations make water unattractive and have a potential impact on the neurological system (Koley. 2021).

Salinity and hardness

Excessive levels of total dissolved solids and hardness in water cause kidney stones, heart and blood vessel problems, and stomach upsets (Ahada & Suthar.2019). Increased levels of sodium also pose a threat, especially for people suffering from hypertension or heart conditions (Yadav et al.2019).

5 Health Risk Assessment

For assessing the health risks associated with groundwater contamination, the hazard quotient (HQ) and hazard index (HI) are often employed as measures of noncarcinogenic risk, while the cancer risk (CR) is applied to those substances that are known to induce carcinogenicity (Khandaker & Rahman.2022). If the HQ or HI is greater than or equal to 1, it indicates that a particular compound poses a potential health risk. In different regions of India, it has been reported that the HI value is greater than unity for 71 to 78% of groundwater samples contaminated with fluoride and nitrate (Marghade et al.2023). Estimated cancer risks in areas contaminated by arsenic often approach and even surpass the acceptable limit of 10^{-4}, where about Several regional health risk assessment studies have reported that approximately 60–80% of analyzed groundwater samples in arsenic-affected regions exceeded the acceptable carcinogenic risk threshold. (Gupta et al.2015). This also emphasizes the seriousness of the long-term risks of arsenic exposure through drinking water and the need to address the problem. Children are also at a higher risk than adults because they weigh less and drink more water per kilogram of weight than adults (Singh et al.2024). Other vulnerable groups, like pregnant women, elderly people, and people with weakened immune systems, are also more susceptible to health risks and, therefore, need special consideration in assessing health risks and planning for water management (Awasthi et al. 2021). Figure 5 illustrates the major routes by which groundwater contamination translates to human health effects. Considering the health hazards associated with groundwater contamination, the need for remediation and treatment of the groundwater arises. The next section highlights the different technologies that can be used in mitigating groundwater contamination in India. For assessing the health risks associated with groundwater contamination, the hazard quotient (HQ) and hazard index (HI) are often employed as measures of noncarcinogenic risk, while the cancer risk (CR) is applied to those substances that are known to induce carcinogenicity. Comparative evaluation of reviewed studies indicates that fluoride and arsenic contamination generally contribute the highest non-carcinogenic and carcinogenic health risks in Indian groundwater systems. Fluoride-related hazard index (HI) values greater than 1 have frequently been reported in semi-arid and hard rock regions of Rajasthan, Telangana, Karnataka, and Tamil Nadu, particularly among children due to lower body weight and higher water intake rates. Similarly, arsenic-contaminated groundwater in eastern India, especially West Bengal and Bihar, consistently shows elevated carcinogenic risk values exceeding the acceptable USEPA risk threshold of 10^{-4}. In contrast, nitrate-associated health risks are comparatively more localized and strongly linked with agriculturally intensive regions such as Punjab, Haryana, and Gujarat. The reviewed literature therefore suggests that health risks from groundwater contamination in India are highly region-specific and controlled by both hydrogeological conditions and anthropogenic activities.

6. Water Quality Standards and Indices

Groundwater quality assessment entails its comparison with drinking water standards to ascertain its suitability for domestic consumption and other uses. These standards are guidelines for establishing benchmark values for water quality, which are used for the evaluation, regulation, and management of water quality. Besides individual parameter analysis, water quality indices are also employed to integrate two or more parameters into a single value, which is a measure of water quality in general.

Regulatory Standards

Groundwater quality standards are determined by different national and international organizations, with the aim of protecting public health and providing safe drinking water. In India, the Bureau of Indian Standards (BIS) specifies the limits of safe and permissible concentrations of drinking water quality, and the World Health Organization (WHO) specifies the global reference values for the same. The United States Environmental Protection Agency (USEPA) specifies the guideline values, which are often used as a reference by researchers in their studies. These guidelines specify the threshold concentrations of major ions, nutrients, heavy metals, etc., present in the groundwater. These limits are critical in order to avoid health risks associated with the long-term use of groundwater (Krishnappa et al. 2024). Table 4 summarizes the permissible limits recommended by BIS, WHO, and USEPA for key groundwater quality parameters.

Table 4: Permissible Limits for Groundwater Quality Parameters (Krishnappa et al., 2024)

Parameter	Unit	BIS (IS10500:2012)	WHO (2017)	USEPA (2018)	Health Significance
pH	-	6.5-8.5	6.5-8.5	6.5-8.5	Corrosion, taste
TDS	mg/L	500 (2000) *	1000	500	Taste, scaling
Total Hardness	mg/L	200 (600) *	500	-	Scaling, cardiovascular
Fluoride	mg/L	1.0 (1.5) *	1.5	4.0	Fluorosis
Nitrate	mg/L	45	50	45	Methemoglobinemia
Arsenic	µg/L	10	10	10	Cancer, Arsenicosis
Lead	µg/L	10	10	15	Neurological damage
Cadmium	µg/L	3	3	5	Kidney damage
Chromium	µg/L	50	50	100	Cancer
Iron	mg/L	0.3	-	0.3	Aesthetic, taste

Table No 4 Adapted from Bureau of Indian Standards (IS 10500:2012), World Health Organization (2017), and USEPA (2018)

***Values in parentheses indicate maximum permissible limits in absence of alternate sources**

Water Quality Index (WQI)

The Water Quality Index (WQI) is a method to represent the overall water quality of groundwater with a single number, obtained by calculating several physicochemical parameters (Hanse et al.2019). By integrating multiple water quality factors, the Water Quality Index simplifies complex information for decision-makers and water resource managers. Among the various methods available, the weighted arithmetic index method is the most popular method used in Indian groundwater research due to its ease and efficiency However, significant methodological variability exists among WQI studies conducted across India. Different researchers have used different combinations of physicochemical parameters, weighting schemes, normalization approaches, and classification criteria depending on regional hydrogeological conditions and study objectives. While some studies considered only major physicochemical parameters such as pH, TDS, hardness, fluoride, and nitrate, others additionally incorporated heavy metals, microbiological indicators, or irrigation-related parameters. Similarly, the relative weights assigned to parameters vary considerably among studies, which directly influences the final WQI values and classification categories. Therefore, direct comparison of WQI values across different regions should be interpreted cautiously, as methodological differences may contribute to variations in reported groundwater quality classifications. (Mukherjee & Singh. 2022). The construction of WQI entails four major stages, which include the selection of appropriate water parameters, assigning weights to each parameter depending on their relative importance in ensuring safe water for human consumption, determining individual water quality ratings, and finally, integrating all ratings to form a single index value (Sahoo et al.2024). The parameters with higher health effects, e.g., nitrates, fluoride, and TDS, have higher weights in the equation. After determining the WQI, groundwater is normally grouped into five classes of water quality, namely, excellent (<50), good (50-100), poor (100-200), very poor (200-300), and not suitable for consumption (>300) (Ravindra & Mor. 2019). Several reviewed studies have reported that a considerable proportion of groundwater samples fall within the “good” water quality category; however, the reported percentages vary depending on the adopted WQI methodology, parameter selection, weighting scheme, and classification criteria used in different studies. While 15-30% lie in the poor to very poor range. Higher values of WQI are recorded in industrial and arid zones, while better water quality is recorded in zones with higher rates of recharge (Adimalla et al.2018). The areas where the water quality index (WQI) is higher are the areas where industries are located, farming is done, and where the climate is arid to semi-arid (Ahada & Suthar.2019). It is worth noting that the differences in the percentages and concentration range reported by different studies can be attributed to differences in spatial coverage, sampling frequency, and methods of analysis. Thus, the data presented in this review is best interpreted as trends rather than exact national data. Further studies need to be undertaken on standardized data collection methods and statistical aggregation.

Most of the studies have used normalized groundwater quality parameters against standard guideline values like BIS (IS 10500) and WHO limits. In the present review, the results have been interpreted in relation to standard values instead of comparing the actual values from different studies, which makes it easy for evaluation (Krishnappa et al.2024). The WQI trends summarized in this review are therefore intended to provide indicative comparative assessment of groundwater quality conditions across regions rather than standardized national-scale WQI rankings.

Table 5: Major Groundwater Contaminants and Associated Health Effects

Contaminant	Sources	Affected Regions	Concentration Range	Health Effects	Indicative Population Exposure	Authors
Fluoride	Geogenic (granite, gneiss weathering)	Rajasthan, Tamil Nadu Andhra Pradesh, Karnataka, Madhya Pradesh	1.5-12 mg/L	Dental fluorosis, skeletal fluorosis, neurological effects	66 million	Das et al.2009, Ghosh et al.2024, Gupta et al. 2019
Arsenic	Geogenic (Fe-oxyhydroxide reduction)	West Bengal, Bihar, Uttar Pradesh, Assam, Chhattisgarh	10-3200 µg/L	Arsenicosis, skin lesions, cancer (skin, lung, bladder)	Estimated from regional studies and published assessments	Gupta et al.2015 , Cherukumilli et al.2018, Inaniyan & Raychoudhury. 2019
Nitrate	Agricultural fertilizers, sewage, animal waste	Punjab, Haryana, Gujarat, Tamil Nadu, Delhi NCR	45-300 mg/L	Methemoglobinemia (infants), gastric cancer, thyroid disorders	Estimated from regional agricultural groundwater studies	Marghade et al.2023, Kumar et al. 2017, Mandal & Sanyal,

						2019
Heavy Metals (Pb, Cd, Cr, Cu, Zn)	Industrial effluents, mining, E-waste	Gujarat, Maharashtra, West Bengal, Jharkhand, Tamil Nadu	Variable (exceeding limits)	Neurological damage, kidney dysfunction, cancer, developmental disorders	Localized population exposure reported	Singh et al.2024, Awasthi et al.2021, Khandaker & Rahman, 2022
Salinity (High TDS, Cl^{-})	Seawater intrusion, evaporation, mineral dissolution	Coastal regions (Gujarat, Tamil Nadu, Kerala, Goa), arid zones	TDS: 1500-5000 mg/L	Kidney stones, cardiovascular issues, gastrointestinal disorders	35-45 million	Ahada & Suthar, 2019, Hussain et al. 2012

Table No 5 Population Estimates are indicative and derived from multiple regional studies. Actual values may vary depending on spatial and temporal factors. Population estimates presented in Table 5 are indicative values compiled from multiple regional investigations and published assessments rather than standardized national-scale datasets.

Table 6: Water Quality Index (WQI) Classification and Interpretation

WQI Range	Water Quality Category	Suitability for Drinking	Treatment Required	Typical Characteristics	% of Indian Samples	Authors
<50	Excellent	Suitable without treatment	None	All parameters well within limits	15-25%	Hanse et al. 2019, Mukherjee & Singh, 2022, Sahoo et al. 2024
50-100	Good	Suitable with minimal treatment	Simple disinfection	Most parameters within limits	40-64%	Hanse et al. 2019, Mukherjee & Singh. 2022 Sahoo et al. 2024
100-200	Poor	Requires treatment	Conventional treatment	Some parameters exceed limits	8-35%	Ravindra & Mor.2019, Adimalla et al.2018
200-300	Very Poor	Requires advanced treatment	Advanced treatment needed	Multiple parameters exceed limits	2-15%	Ravindra & Mor, 2019, Adimalla et al. 2018 Ahada & Suthar.2019)

>300	Unsuitable	Not suitable for drinking	Extensive treatment/alternate source	Severe contamination	3-11%	Ravindra & Mor. 2019, Adimalla et al.2018 Ahada & Suthar.2019

Table No 6 Percentage ranges represent compiled estimates from multiple regional studies and may vary depending on hydrogeological conditions, sampling methods, and spatial coverage. These values represent compiled trends from reviewed regional studies and not national-scale statistical estimates

Table 7 Comparative Health Risk Trends Reported in Indian Groundwater Studies

Contaminant	Dominant Risk Type	Most Vulnerable Regions	Commonly Affected Population	Reported Risk Trend	References
Fluoride	Non-carcinogenic (HI > 1)	Rajasthan, Telangana, Karnataka, Tamil Nadu	Children	Very High	Das et al. 2009, Ghosh et al. 2024, Gupta et al. 2019, Ahada & Suthar.2019
Arsenic	Carcinogenic ($CR > 10^{-4}$)	West Bengal, Bihar, Assam	General population	Very High	Gupta et al. 2015, Cherukumilli et al. 2018, Inaniyan & Raychoudhury. 2019
Nitrate	Non-carcinogenic	Punjab, Haryana, Gujarat	Infants	Moderate–High	Kumar et al. 2017, Mandal & Sanyal. 2019,

					Marghade et al. 2023
Heavy Metals	Carcinogenic and non-carcinogenic	Industrial and mining regions	Adults and children	Moderate	Singh et al. 2024, Awasthi et al. 2021, Khandaker & Rahman. 2022
Salinity/TDS	Chronic exposure-related risk	Coastal and arid regions	General population	Moderate	Ahada & Suthar. 2019, Hussain et al. 2012

Table 7. Comparative health-risk trends synthesized from published regional groundwater assessment studies conducted across different hydrogeological settings in India.

7 Integrated Assessment Framework for Groundwater Quality in India

Based on the synthesis of the literature, an integrated framework has been proposed for connecting groundwater contamination sources, hydrogeochemical processes, health risks, and remediation strategies in the Indian context (Mukherjee & Singh.2022, Malik et al.2023). Both anthropogenic and geogenic sources of groundwater contamination have been identified, and the hydrogeochemical processes influencing groundwater quality have also been analysed (Singh et al.2022, Yadav et al.2018). Human health risks from groundwater contamination have also been discussed in the framework. Remediation strategies have also been included in the framework for addressing groundwater contamination in the Indian scenario. This framework will help in understanding groundwater contamination in a better way for sustainable groundwater management in the country. This integrated framework represents a novel contribution of this review by linking contamination sources, hydrogeochemical processes, health risks, and remediation strategies in a unified manner.

8 Remediation Strategies

The diagram presents the Integrated Remediation Technology Framework for Indian Groundwater. It is a decision guide to select appropriate cleanup technologies based on the nature of the contaminant, concentration of the contaminant, scale of the problem, and social and economic factors. The framework includes source control technologies, in-situ technologies like PRBs and phytoremediation, ex-situ technologies like RO, adsorption, and electrocoagulation, and monitoring technologies to address the issue of groundwater in a holistic manner. Figure 6 demonstrates that selection of groundwater remediation technologies depends on contaminant type, contaminant concentration, treatment scale, economic feasibility, and operational complexity. The framework indicates that advanced membrane technologies are highly effective for multi-contaminant removal but are associated with high operational cost and energy demand. In contrast, adsorption-based and nature-based technologies are more suitable for decentralized rural applications because of lower operational requirements and improved sustainability.

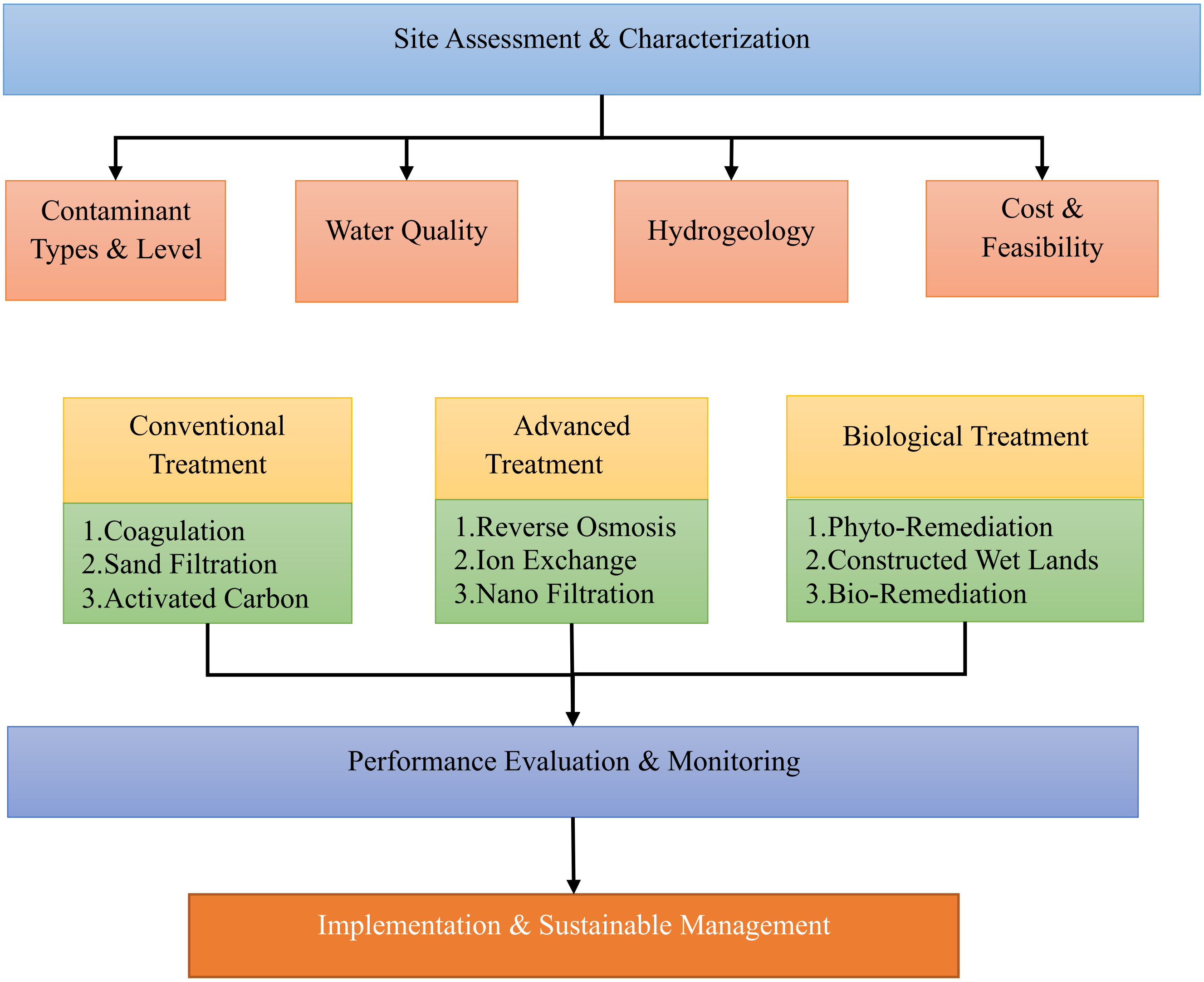

Figure 6. Framework for selection of groundwater remediation technologies based on contaminant type and site conditions.

9. Conventional Treatment Technologies

Reverse Osmosis (RO)

Reverse osmosis has emerged as a preferred treatment technology for groundwater in India, thanks to its high removal capabilities for a wide array of impurities. In this method, water is pressurized to pass through a semi-permeable membrane, resulting in a reduction of fluoride levels by 85-95%, arsenic by 90-98%, nitrate by 85-92%, heavy metals by 90-99%, and total dissolved solids by 95-98%. RO systems have been found to be highly effective and are used across residential, institutional, and community water treatment systems. However, there are some negative aspects to this technology, such as high energy requirements, membrane fouling, and maintenance, and the difficulty of handling the reject brine water. The cost of the equipment varies widely, from ₹5,000 to ₹25,000 for household systems to ₹5 to ₹50 lakhs for community systems (Muthusamy et al. 2023).

Nanofiltration (NF)

Nanofiltration operates at lower pressures compared to reverse osmosis treatment. The process has a strong ability to remove divalent ions, organic matter, and a certain amount of dissolved solids. The process has a removal efficiency of 70-85% (Nagaraj & Masilamani,.2023). The process is effective in reducing hardness, sulphates, and some fluoride in groundwater supplies. Due to the low energy consumption and less brine disposal compared to reverse osmosis, the process is regarded as a cost-effective solution for brackish water treatment *(*Bhuiyan & Ray.2017).

Activated Alumina Adsorption

Activated alumina is frequently utilized for the adsorption-based removal of fluoride and arsenic from water. It has been seen to remove fluoride to the extent of 80 to 90%, and arsenic to the extent of 75 to 85%. However, this depends on the water being treated (Yasaswini et al. 2024). The method is preferred for its simple design, easy operation, and low cost, estimated to be between ₹2,000 and ₹10,000. domestic-scale treatment. However, its effectiveness is pH-dependent, and regeneration or replacement is required periodically (Mukherjee et al. 2021).

Ion Exchange

Ion exchange resins selectively extract impurities, like fluoride, nitrates, and heavy metals, from groundwater. The method usually eliminates 85-95% of impurities, depending upon the type of resin and water quality (Thalod & Sharma.2024). However, ion exchange resins also have a drawback, as their periodic regeneration is necessary using chemical solutions, leading to a disposal problem. The effectiveness of ion exchange resins is also restricted by the lack of proper disposal facilities for solid wastes (Mandal & Sanyal.2019).

10 Advanced and Emerging Treatment Technologies

Electrocoagulation

Electrocoagulation has been proven as a viable electrochemical technique in the treatment of groundwater contaminated by fluoride, arsenic, heavy metals, and suspended solids. In this technique, coagulating species are in situ produced through the sacrifice of dissolving electrodes, which operates in the range of 75–90% for fluoride, 80–95% for arsenic, and 85–98% for heavy metals. The primary advantages of this technique include the elimination of the need for chemical dosing, a compact design, and low levels of sludge formation. However, the technique has some limitations in real-world application, which include energy consumption (0.5–3 kWh/m^3), electrode passivation, and the need for electrode replacement (Kalaiselvi & Pillai.2019, Vijaylaxmi & Khan. 2021).

Adsorption – Based Technologies

Recently, breakthroughs in adsorption technology have led to the development of a new list of high-performing adsorbents for groundwater treatment. Biochar, clay, metal oxide, and complex nanostructured adsorbents have shown promising adsorption capacities for the removal of fluoride, arsenic, and various heavy metals, ranging from 80 to 99% effective (Saha et al.2014). Of specific interest are adsorbents made from agricultural waste materials, which are rice husk, coconut shells, and neem leaves, and are gaining popularity as a cost-effective, green technology solution for groundwater treatment in rural communities (Karunanidhi et al.2024). However, there are still challenges in the adsorption process, which include the regeneration of the adsorbents, the adsorbent's lifespan, and the disposal of the exhausted adsorbents, which need further optimization (Kumar et al.2017).

Phytoremediation

Phytoremediation utilizes the natural uptake of pollutants by plants, thereby purifying water and soil. Water-loving plants, like the water hyacinth, duckweed, and vetiver, and those on land, like the sunflower, mustard, and ferns, have been observed to uptake heavy metals, nutrients, and organic chemicals (Muthusamy et al. 2023). It offers an eco-friendly and cost-effective approach for the remediation of shallow aquifers, groundwater with links to surface water, and constructed wetlands (Nagaraj & Masilamani.2023). However, its application is restricted by the low rate of cleanup, seasonal fluctuations, and the management and disposal of the polluted vegetation (Bhuiyan & Ray.2017).

Membrane Bioreactors (MBRs)

Membrane bioreactors utilize the combination of a biological process and membrane filtration for the effective removal of organic matter, nutrients, and pathogens (Yasaswini et al.2024). The process has been found to be effective in the treatment of polluted groundwater and wastewater intended for aquifer recharge and reuse. The process has the advantage of high treatment efficiency in a space-saving design; however, the problem of membrane fouling and the operating costs need to be taken into consideration (Mukherjee et al.2021).

Permeable Reactive Barriers

The permeable reactive barrier (PRB) technology is an innovative groundwater remediation technology. In the PRB technology, the contaminated groundwater is treated with the help of a reactive medium such as zero-valent iron, activated carbon, or limestone (Thalod & Sharma.2024). The groundwater flows through the medium and is treated. The technology has been found to treat heavy metals, chlorinated organic compounds, and nutrient compounds (Cherukumilli et al.2017).

Technology Selection and Implementation

The choice of technology is based on the type of contaminant present and the amounts present, the quality characteristics of the water to be treated, the scale of the treatment (residential, community, or regional), cost viability, the complexity of the technology, and the capacity that is observed locally (Kalaiselvi & Pillai.2019). Table 8 shows the various remediation technologies lined up. In most cases, the best results are achieved by combining different technologies into a hybrid technology. For the technologies to bear fruit, the community needs to be engaged with capacity building and sustainable funding models. In rural and disadvantaged areas, policy support, subsidies, and awareness are key to the use of the technologies. Comparative evaluation of groundwater remediation technologies indicates that no single treatment method is universally suitable for all groundwater contamination conditions in India. Reverse osmosis demonstrates the highest overall removal efficiency for fluoride, arsenic, nitrate, salinity, and heavy metals; however, its large energy requirement, membrane fouling, and reject brine disposal significantly limit its applicability in economically weaker rural regions. Nanofiltration provides comparatively lower operational pressure and energy consumption but is less effective for complete dissolved contaminant removal. Adsorption-based technologies using activated alumina, biochar, and modified low-cost materials are considered more suitable for rural and decentralized applications because of their lower cost, operational simplicity, and minimal energy requirements, although periodic adsorbent regeneration and disposal remain important operational concerns. Electrocoagulation has shown promising removal efficiency for fluoride, arsenic, and heavy metals, but field-scale implementation is constrained by electrode passivation, electricity demand, and sludge management requirements. Similarly, ion exchange systems provide effective selective contaminant removal but generate secondary brine waste requiring appropriate disposal. Therefore, technology selection in the Indian context should consider contaminant type, hydrogeochemical conditions, treatment scale, operational complexity, waste disposal requirements, energy availability, and socio-economic feasibility, particularly in rural and resource-limited regions.

Table 8: Comparison of Groundwater Remediation Technologies

Technology	Target Contaminants	Removal Efficiency	Capital Cost	Operating Cost	Advantages	Limitations	Rural Applicability	Authors
Reverse Osmosis	Fluoride, arsenic, nitrate, heavy metals, TDS	85-98%	High (₹5,000-50L)	High	High efficiency, multiple contaminants	Energy intensive, brine disposal	Moderate	Muthusamy et al., 2023, Nagaraj & Masilamani, 2023, Bhuiyan & Ray.2017
Activated Alumina	Fluoride, arsenic	75-90%	Low (₹2,000-10,000)	Low	Simple, low cost	pH dependent, regeneration	High	Yasaswini et al.2024, Mukherjee et al.2021
Electrocoagulation	Fluoride, arsenic, heavy metals	75-98%	Moderate (₹10,000-5L)	Moderate	No chemicals, compact	Electrode replacement, energy	Moderate	Kalaiselvi & Pillai, 2019, Vijaylaxmi & Khan. 2021
Adsorption (Biochar, modified materials)	Fluoride, arsenic, heavy metals	80-99%	Low (₹1,000-8,000)	Very low	Low cost, sustainable	Regeneration, disposal	Very High	Saha et al.2014, Karunanidhi et al. 2024, Kumar et

								al. 2017
Phytoremediation	Heavy metals, nutrients, organics	60-85%	Very low (₹500-5,000)	Very low	Eco-friendly, sustainable	Slow, seasonal, biomass disposal	High	Muthusamy et al. 2023, Nagaraj & Masilamani, 2023, Bhuiyan & Ray, 2017
Ion Exchange	Fluoride, nitrate, heavy metals	85-95%	Moderate (₹5,000-20,000)	Moderate	Selective removal	Brine disposal, regeneration	Moderate	Mandal & Sanyal, 2019, Thalod & Sharma.2024
Nanofiltration	Hardness, sulphate, moderate TDS	70-85%	Moderate-High (₹8,000-30L)	Moderate	Lower pressure than RO	Partial removal	Low–Moderate	Nagaraj & Masilamani.2023, Bhuiyan & Ray. 2017

Table 8. Synthesized from groundwater treatment and remediation studies. Cost ranges are indicative and may vary depending on system capacity, location, and operational conditions. Rural applicability assessment presented in Table 8 is based on operational simplicity, energy requirements, maintenance demand, waste disposal complexity, and economic feasibility reported in reviewed studies.

11 **Future Perspectives and Research Directions**

Emerging Research Priorities

Future areas of research should address the following gaps in the knowledge of the quality of groundwater in India. Some of the areas that need priority in the future are the following: the emerging contaminants in the groundwater, which include pharmaceuticals, pesticides, microplastics, and PFAS (Pal et al.2009, Sultan et al.2024). There is a pressing need for treatment technologies that are cost-effective, energy-efficient, and adaptable to local conditions, especially in rural areas (Karunanidhi et al. 2024). Advances in monitoring and forecasting can be achieved through integrating technologies of remote sensing, GIS, and machine learning, which will facilitate real-time continuous evaluation of groundwater quality (Thalod & Sharma.2024). Moreover, the impacts of climate change on groundwater recharge, the mobilization of contaminants, and the long-term trends in water quality require special research attention (Kaur et al., 2019). The research focus of the health sector needs to move beyond the examination of individual factors to the evaluation of the collective impacts of the risks that arise from the joint action of various contaminants (Khandaker & Rahman. 2022). Moreover, the role of managed aquifer recharge (MAR) as a two-fold approach to enhancing groundwater quality and increasing its storability needs to attract more research attention on a regional scale (Dhakshinamoorthy & Selvarajan.2025). Based on the trends in groundwater quality being reported from different regions of India, it has been assessed that regions with high intensity in agricultural practices and groundwater depletion will have high nitrate and salinity problems in the near future (Kaur et al.2019, Kumar et al.2017). Similarly, changes in recharge patterns due to climate variability will enhance the mobilization of geogenic contaminants like fluoride and arsenic in groundwater (Dhakshinamoorthy & Selvarajan.2025).

12 Policy and Management Recommendations

For effective groundwater quality management in India, it is significant to adopt a multi-tier strategy. Strengthening the regulatory system and enforcement of regulations are significant steps towards curbing pollution caused by agricultural, industrial, and urban activities (Shukla & Saxena.2021). Preventive measures should focus on source control, including the adoption of sustainable agriculture, better management of industrial effluent disposal, and scientifically disposing of solid and liquid waste (Kumar et al.2017). A robust, all-inclusive groundwater quality monitoring system is vital, which is supported by real-time data collection and information sharing among various regulatory agencies, scientists, and local governments (Gupta et al.2022). Community engagement must be encouraged through decentralized water quality management, monitoring, and capacity-building programs to empower people to protect and manage groundwater resources (Hossain et al. 2021). Financial incentives, subsidies, and technical support are also necessary to promote the use of water treatment systems at the individual and community levels, especially in rural and disadvantaged areas (Karunanidhi et al.2024). Another significant factor is to enhance public awareness of groundwater contamination issues and the associated health risks with the help of effective educational campaigns (Das et al. 2009) Ultimately, the key to sustainability is to enhance inter-disciplinary research and cooperation between policymakers, scientists, and stakeholders to develop effective groundwater management strategies that are tailored to specific contexts (Kaliyan et al.2022).

Technological Innovations

Recent advances in groundwater management reveal some promising tech avenues. Nanotechnology adsorbents and membrane filtration have demonstrated better efficacy in removing a range of impurities, from fluoride and arsenic to heavy metals (Saha et al. 2014). In energy-scarce environments, solar-powered water treatment could be a viable solution for reliable operation in a rural setting (Muthusamy et al. 2023). Real-time groundwater quality monitoring is being strengthened with the help of smart sensor technologies. IoT technology, for instance, helps in the rapid detection of changes in the quality of water with the help of IoT-powered water quality monitoring systems. Simultaneously, AI and machine learning techniques are being used for the prediction and assessment of groundwater quality (Thalod & Sharma.2024). Nature-based and hybrid technologies, like constructed wetlands and bioremediation, are gaining prominence as they operate with low operating costs and in a highly environmental-friendly manner (Nagaraj & Masilamani.2023). Decentralized treatment technologies, which are designed for households and communities, also hold promise as a solution for groundwater pollution, especially in rural areas (Karunanidhi et al.2024).

Sustainable Water Resource Management

Ensuring the sustainability of groundwater resources for the long run requires a linked water resources approach that connects demands, supplies, and ecosystems. In terms of cutting back on water use, the focus should be on saving water, improving irrigation efficiency, and enhancing the efficiency of water use (Prasad & Rao.2018). In terms of supplying more water, the focus should be on harvesting rainwater, recharging groundwater, and safely reusing treated water to enhance groundwater supplies while lessening the pressure on natural groundwater supplies (Dhakshinamoorthy & Selvarajan.2025). The key to the prevention of further deterioration in the quality of groundwater lies in the effective control of pollution, which includes the reduction of pollution, the application of best management practices, and the enforcement of environmental laws (Kumar et al.2017). Another important factor is the protection and maintenance of ecosystems that rely on groundwater, which is necessary to maintain the quality of the water itself (Nagaraj & Masilamani.2023*)*. Sustainable water management should be equitable, ensuring everyone has access to water that is safe and reliable, particularly for vulnerable and marginalized groups (Rajendran et al.2024). As the climate changes, with shifts in rainfall, droughts, and increasingly extreme events, water management strategies should be responsive to these changes to create long-term sustainability (Kaur et al.2019). Reaching the Sustainable Development Goal for water and sanitation, SDG 6, requires collaboration and coordination among government agencies, scientists, businesses, and social organizations (Shukla & Saxena.2021).

13. Limitations of Existing Studies

Although extensive research has been done regarding the quality of groundwater resources in India, certain limitations have been identified with the existing research. One major limitation is that the research is localized and based on limited sample size This limits the research to be representative (Hanse et al.2019), (Mukherjee & Singh.2022). Another limitation is that long-term monitoring data are not available This limits the understanding of the trends over time (Mawari et al.2022). Another limitation is that the sampling and analysis techniques have been inconsistent (Ahada & Suthar. 2018). These limitations show that current groundwater research in India is not well organised and is not standardised, which makes it hard to come up with integrated and policy-relevant strategies for managing groundwater. So, we need big, standardised monitoring programs, consistent ways to analyse data, and long-term datasets so that we can reliably compare and predict groundwater quality.

Data Variability and Comparability Considerations

Integrating the groundwater quality data from various studies may pose difficulties due to the inconsistencies in spatial distribution, time scales, and methodologies. The hydrogeological conditions, such as the presence of alluvial or hard rock formations, affect the movement of water and the presence of impurities. Although the review has provided an integrated overview of the groundwater quality trends in India, the results must be considered indicative rather than exact quantitative data (Mawari et al.2022, Ahada & Suthar.2018). Population exposure estimates and contamination percentages reported in the reviewed literature are derived from regional investigations conducted under different hydrogeological and methodological conditions and should therefore be interpreted as indicative estimates rather than precise national-scale statistics.

Integrated Perspective on Groundwater Contamination

Groundwater contamination in India is a multifaceted phenomenon involving the interrelationship between sources of contamination, hydrogeochemical processes, and human health impacts (Mukherjee & Singh. 2022, Malik et al.2023). Human activities like agriculture, industrial discharge, and urbanization are sources of groundwater contamination in India, while hydrogeochemical processes play an important role in groundwater chemistry, increasing the concentration of contaminants like fluoride, arsenic, nitrate, and heavy metals in groundwater. Human health impacts of groundwater contamination in India are significant, considering the high concentration of contaminants in groundwater. Therefore, groundwater management in India involves an interrelationship between sources of contamination, groundwater chemistry, human health impacts, and appropriate measures for groundwater remediation.

14. CONCLUSIONS

India’s groundwater is a complex patchwork, and its quality is determined by a combination of rock, climate, and human factors. When viewed region-wise, there are specific areas of contamination. Fluoride is observed in many states, arsenic is a major threat in eastern states, nitrates are present in areas of high agricultural activity, and heavy metals are found in areas of industrial activity. When viewed as a whole, a major share of the population is impacted by groundwater contamination, which is a threat to long-term health and sustainability. When physicochemical parameters are examined, a large number of groundwater samples indicate a level of contamination in terms of total dissolved solids, hardness, and nitrates, which indicates a combination of natural and anthropogenic factors. The level of contamination is a result of a combination of geogenic factors, which include rock-water interaction and redox reactions, as well as anthropogenic factors, which include excessive use of fertilizers, industrial effluents, poor sewage disposal, and mining activity. Health risk assessments indicate a high level of non-carcinogenic as well as carcinogenic risks in areas of contamination. Fluorosis, arsenic toxicity, methemoglobinemia, and heavy metal toxicity are major public health concerns, especially in children. The Water Quality Index results indicate that a part of the groundwater is potable, but a major share of it needs to be treated or an alternative source of water needs to be found. There are several options for remediation and treatment, including membrane systems, adsorption, electrochemical treatments, and nature-based solutions, among others, even though none of these options are universally applicable. It should be noted, however, that effective action will involve matching the contaminant profile, water chemistry, scale, cost, and local technical capacity. The present review demonstrates that groundwater contamination in India exhibits strong regional variability controlled by hydrogeological conditions, climatic factors, land-use practices, and anthropogenic pressures. Arsenic contamination remains the most critical concern in the eastern alluvial aquifer systems because of its severe carcinogenic risks and widespread population exposure. In contrast, fluoride contamination dominates the hard-rock terrains of western and southern India, where prolonged groundwater residence time and rock–water interaction enhance fluoride mobilization. Nitrate contamination is primarily associated with agriculturally intensive regions of northern and western India, indicating the growing influence of unsustainable fertilizer usage and poor sanitation practices. Heavy metal contamination is more localized and concentrated near industrial and mining regions, particularly in central and western India. These observations indicate that groundwater management strategies in India should be region-specific rather than adopting a single uniform national approach. From a management perspective, priority should be given to strengthening regional groundwater quality monitoring networks, promoting source-control strategies, improving rural drinking-water treatment infrastructure, and implementing sustainable agricultural and industrial practices. Cost-effective decentralized treatment systems and community-based groundwater management approaches are particularly important for rural and economically weaker regions. The review also identifies several important research gaps, including insufficient long-term monitoring datasets, limited studies on emerging contaminants, lack of standardized groundwater quality assessment methodologies, and inadequate integration of hydrogeochemical modeling with health-risk assessment frameworks. Future research should focus on multidisciplinary approaches integrating hydrogeochemistry, GIS, remote sensing, machine learning, and climate-change assessment to support sustainable groundwater management and policy development in India. In the future, it will be important to focus on the understanding of emerging contaminants, the development of cost-effective treatment options, the development of advanced monitoring and prediction tools, and the assessment of the impact of climate change on groundwater quality, among other things. It should be noted that the synthesis of the above will be important in the decision-making process of researchers, policymakers, water managers, and public health professionals, among other individuals. Tackling the issue of groundwater quality degradation in India is important in the future.

Author Contributions

Sanap Santosh Tukaram contributed to the conceptualization of the manuscript, Systematic literature collection, data compilation, analysis, and preparation of the original draft manuscript.

Dr. Shrikant Bhausaheb Randhavane & Dr. Narayan Ratanlalji Chandak contributed to the study design, supervision, critical revision of the manuscript, and improvement of technical content, final editing and approval of the manuscript.

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Conflict Of Interest

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